I-V and C-V characteristics of rare-earth-metal/p-GaN Schottky contacts

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Received zzz, revised zzz, accepted zzz
Published online zzz (Dates will be provided by the publisher.)

PACS 73.30.+y, 73.40.-c, 73.40.Sx, 73.61.Ey

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The electrical properties of rare-earth-metal Schottky contacts to p-GaN were characterized with current-voltage (I-V) and capacitance-voltage (C-V) measurements for the first time. Three kinds of rare-earth-metal films of Dy, Er, and Gd, which have low-metal-work-function nature, were deposited on low-Mg-doped p-GaN. Linear regions of more than one and a half orders were seen in a forward semi-log I-V plot, and reverse break down voltages were as high as around 60 V for all samples. In the C-V characteristics, good linearity was obtained in a $1/C^2$ plot for all samples. The carrier concentration was estimated to be about 5.5×10^{16} cm^{-3}, which is a reasonable value of activation efficiency of 4.2%. The Schottky barrier heights of Dy, Er, and Gd contacts were 1.91, 2.38, and 2.16 eV from I-V, and 1.79, 1.78, and 1.70 eV from C-V, respectively. These values are as high as those of the transition metal contacts. These results tell us that Fermi level pinning is significantly strong for p-GaN surfaces with a conventional acid treatment.

1 Introduction The recent progress in GaN-based optoelectronic devices, such blue light-emitting diodes, laser diodes, and ultraviolet detectors, points to the need for better ohmic contacts to p-GaN and a deeper understanding of metal/p-GaN interfaces. In the early days of the device development, process techniques for p-GaN ohmic contacts have been intensively studied including contact metals, annealing methods, and surface treatments [1-3], however, the basic electrical characteristics, such as Schottky barrier height ($q\phi_B$) and current transport mechanism, have not been well understood. For n-GaN Schottky contacts, $q\phi_B$ has been found to basically depend on the metal work function (ϕ_m) due to the ionic nature of GaN [4], and $q\phi_B$ of up to 1.5 eV has been reported [5]. On the other hand, for p-GaN, a much higher $q\phi_B$ (above 2 eV) is expected since the sum of the $q\phi_B$'s of n and p types adds up to the band gap (Eg) of 3.4 eV [6, 7]. In spite of that, conventional p-GaN contacts show leaky and nonrectifying characteristics, consequently the apparent $q\phi_B$ is low (< 1.2 eV) [8, 9] and the current flow mechanism has not been established.

We examined reducing Mg accepter doping concentration in order to suppress leakage current due to a wider depletion layer width (W). The Ni/p-GaN contacts showed good current-voltage (I-V) characteristics and the $q\phi_B$ was as high as 2.4±0.2 eV [10]. Further studies on ϕ_m dependence of $q\phi_B$ were also conducted for transition metal/p-GaN contacts [11].

As for the current transport mechanism, we found that carrier capture and emission from accepter-like mid-gap level defects localized in the vicinity of the interface cause W to vary significantly. Upon ionization of the defects by white light, which results in small W, current can go through the Schottky barrier and a leaky I-V curve is observed. Upon filling by current injection, W becomes larger and the large original $q\phi_B$ is seen [12, 13].

This paper reports electrical characteristics of rare-earth-metal contacts to p-GaN for the first time. Because rare-earth-metals have low ϕ_m nature, an unlikely band line up is expected, i.e., a negative barrier for n-type or a barrier over Eg for p-type contacts. Three kinds of rare-earth-metal contacts of Dy, Er, and Gd were formed on low-Mg-doped p-GaN, and I-V and capacitance-voltage (C-V) characteristics were evaluated. Then, a model for $q\phi_B$ formation and comparison with other experimental results are discussed.

2 Sample preparation and measurement condition Sample structure of rare-earth-metal/p-GaN Schottky contacts is shown in Fig. 1. Low-Mg-doped 2-μm-thick GaN films were grown on (0001) sapphire using metalorganic chemical vapor deposition. A mixture of Biscyclopentadienyl magnesium (CP_2Mg) in H_2 was the Mg precursor. The films were grown at 1075℃ with 25-nm-thick low-temperature (T_G = 450℃) unintentionally doped GaN buffer layers. The Mg concentration was 1.3×10^{18} cm^{-3} according to secondary ion mass spectrometry measurements.

The GaN surface was degreased in acetone and methanol, and then the surface oxide was removed in buffered hydrofluoric acid solution (BHF) prior to loading the samples into the chamber for metal deposition. 100-nm-thick three kinds of metal films (Dy, Er, Gd) were deposited by electron-beam evaporation through a metal mask with 200-μm diameter circular openings to form Schottky contacts. Because rare-earth-metal is easy to oxidize, 100-nm-thick Au caps were consequently deposited. Metal work functions of Dy, Er, and Gd are 3.1, 3.2, and 3.1 eV, respectively. In order to avoid any effect of ohmic sintering to the GaN surface, we used InGa non-alloyed ohmic contacts surrounding the Schottky contacts, and were more than 100 times larger than the Schottky contact in area.

The I-V and C-V measurements were carried out by using an HP4155C semiconductor parameter analyzer and an HP4284A LCR meter, respectively. As mentioned in the introduction section, in order to neutralize the accepter-like mid-gap level defects localized in the vicinity of the interface, large forward current was flown under a bias voltage of -5 V. Just after the neutralization, the I-V and C-V measurements started. The measurement time was much smaller than the time constant of the mid-gap level. The detail measurement procedure was reported in Ref. 12.

The $q\phi_B$ and ideality factors (n-values) were simply calculated in terms of only the thermionic emission model [14] using

$$J = A^{**}T^2\exp\left(-\frac{q\phi_B}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right]. \qquad (1)$$

where A** is the effective Richardson constant (72 A/cm^2K^2 for p-GaN based on $A^{**}=4\pi m^*qk^2/h^3$ and $m^*=0.60m_0$), T is the temperature, q is the charge of the electron, k is the Boltzman constant, and V is the applied voltage.

C-V measurements were also performed at a frequency of 10 kHz. The C-V relationship for a Schottky contact is

$$\frac{1}{C^2} = \left(\frac{2}{\varepsilon q N_a}\right)\left(\frac{V_{bi}-V-kT}{q}\right) .$$

$$\phi_B = V_{bi} + \left(\frac{kT}{q}\right)\ln\left(\frac{N_V}{N_a}\right) . \qquad (2)$$

where ε is the permittivity ($\varepsilon_{GaN}=9.5\varepsilon_0$), N_a is the accepter concentration, and $N_v=1.17\times10^{19}$ cm^{-3} based on $N_v=2(2\pi m^*kT/h^2)^{3/2}$ [15]. Q values (Q=ωC/G) are as high as over 30.

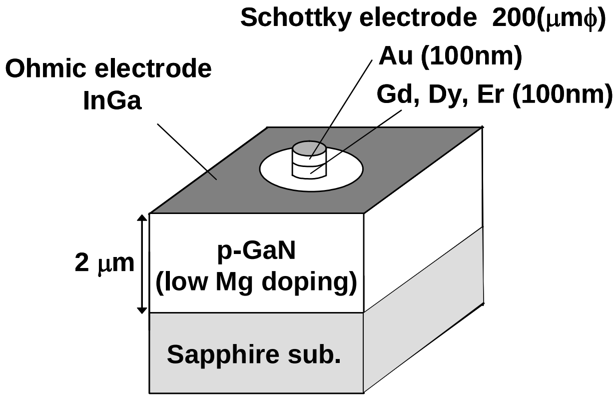

Figure 1 Sample structure of rare-earth-metal/p-GaN Schottky contacts.

3 Experimental results Figure 2 shows typical forward I-V characteristics of all three kinds of Schottky contacts in a semi-log plot. For all the contacts, when a bias voltage is swept from 0 to -2.5 V, the currents are small and gradually increase from 0.3 pA to 2 pA. Below a bias voltage of -2.5 V, the currents rapidly increase and the linear regions of more than one and a half orders are seen. Therefore, the I-V curves mainly consist of a small leakage current and a thermionic emission current over the Schottky barrier. The metal-to-metal variation is small, and when the currents reach at 100 pA the bias voltage are in the range between -2.6 and -3.2 V.

Figures 3 shows typical reverse I-V curves under an applied voltage up to 100 V. The reverse currents are as small as less than 2 pA at 10 V. In the higher voltage region, the reverse currents gradually increase but are quite unstable. Finally, a sudden increase occurred and the contacts broke down catastrophically. The breakdown voltages (V_{br}) of Dy, Er, and Gd contacts were 67.9, 59.6, and 65.5 V, respectively. Concluding the forward and reverse I-V results, great suppression of the leakage was confirmed by the low-Mg-doping.

The C-V measurements were conducted with an applied voltage from 0 to 8 V. The $1/C^2$ plot is shown in Fig. 4. All the contacts showed good linearity based on the Schottky characteristics with a small leakage current. Calculated carrier concentrations was estimated to be 5.5×10^{16} cm^{-3} in average, which is a reasonable value of activation efficiency of 4.2%.

Table 1 shows summarized $q\phi_B$, n-values, and V_{br} from the I-V and C-V measurements with metal work functions. The $q\phi_B$ of Dy, Er, and Gd contacts were 1.91, 2.38, and

2.16 eV from I-V, and 1.79, 1.78, and 1.70 eV from C-V, respectively. These values are as high as those of the transition metal contacts [11]. The n-values were 2.62 for Dy, 2.04 for Er, and 2.18 for Gd contacts. These values are relatively good for p-GaN Schottky contacts. However, they are larger than unity. A tunnelling current might be present due to the existence of accepter-type deep levels, which are much shallower mid-gap levels and can be ionized before the measurements even though the large forward current was injected.

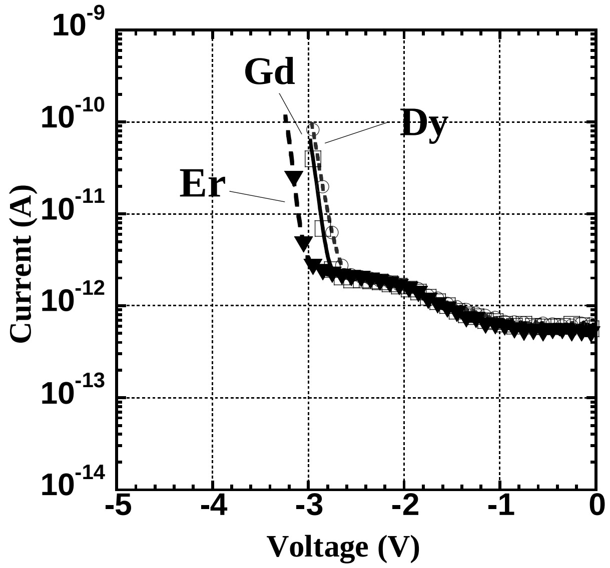

Figure 2 Forward I-V characteristics.

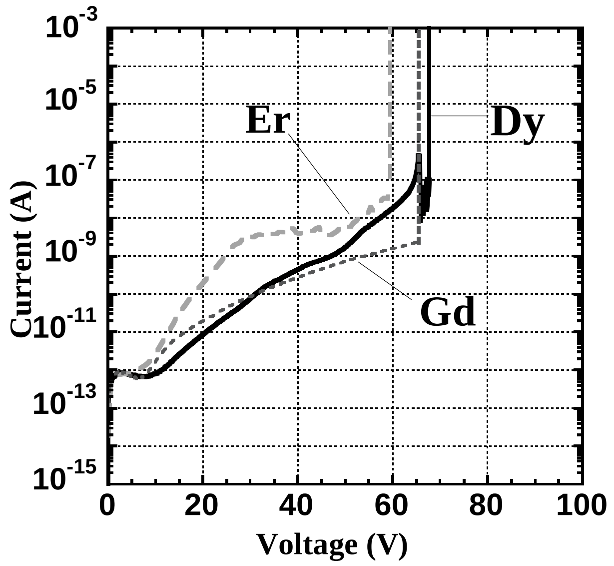

Figure 3 Reverse I-V characteristics.

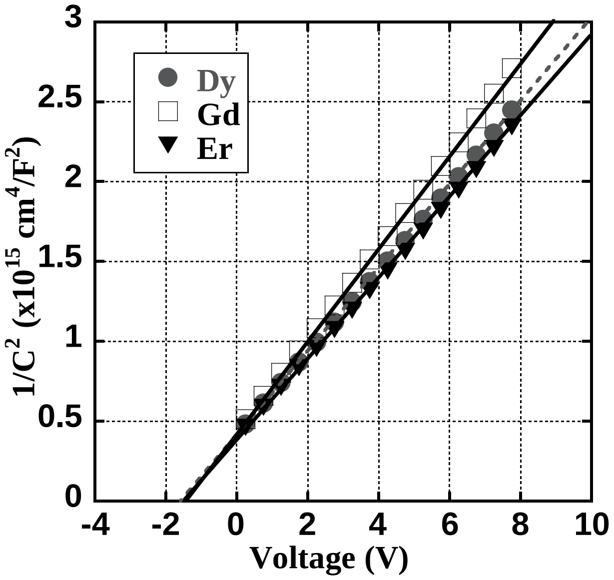

Figure 4 C-V characteristics in a $1/C^2$ plot.

Table 1 Summary of measured electrical characteristics with metal work functions.

Metal deposited	ϕ_m	$\phi_{B,I\text{-}V}$ (eV)	n-value	Break down voltage (V)	$\phi_{B,C\text{-}V}$ (eV)
Dy	3.1	1.91	2.62	67.9	1.79
Er	3.2	2.38	2.04	59.6	1.78
Gd	3.1	2.16	2.18	65.5	1.70

4 Discussion The low-Mg doping successfully suppressed leakage currents, and good I-V and C-V characteristics with high $q\phi_B$ values were obtained from all three kinds of rare-earth-metal contacts. Consequently, the measured electrical properties are discussed from a point of chemical potential difference between metal and GaN. Figure 5 shows ϕ_m dependences of $q\phi_B$ from the I-V and C-V results together with our previous results for the transition metal contacts [11]. From the prediction of the Schottky-Motto model [16], the slope parameter of ϕ_m dependence; $S = \Delta\phi_B/\Delta\phi_m$, is -1 for p-GaN. When the electron affinity of p-GaN is 4.1 eV, the dependence is expected as shown on the gray solid line in Fig. 5. On the other hand, in our results, the $q\phi_B$ is virtually independent of ϕ_m. The S parameter is +0.089 from the I-V (dotted line) and +0.054 from the C-V (black solid line). This indicates that strong Fermi-level pinning occurred in this metal/p-GaN system. Sawada reported I-V characteristics of In, Al, Ag, Au, Ni, Pt contacts formed on medium-doped p-GaN (Mg : 5.0×10^{18} cm^{-3}) with an HCl surface treatment [9]. The measured $q\phi_B$ values were less than 1.3 eV, and the S parameter was -0.2.

On the other hand, Rickert conducted X-ray photoemission measurements for thin-transition-metal/p-GaN contacts with a specific chemical treatment including surface p-GaN etching [17]. The dependence was large and the S parameter was -0.8. One reason for this discrepancy is in the difference of evaluation techniques. Since their carrier concentration ($p = 3.3\times10^{17}$ cm^{-3}) is higher than ours, the electrical characteristics might be leaky. The correlation between the results of X-ray and electrical measurements is required. Another reason is in the surface treatment. It is likely that the p-GaN contacts with a conventional surface treatment using acid solution for native oxide removal show a strong Fermi level pinning. As mentioned in the introduction section, for n-GaN Schottky contacts, even with a conventional surface treatment, the $q\phi_B$ basically depended on ϕ_m with S = 0.7 [4]. It can be considered that the p-GaN surface still has a large amount of surface states comparing with n-GaN. Surface etching might be required to obtain a pinning-free clean surface.

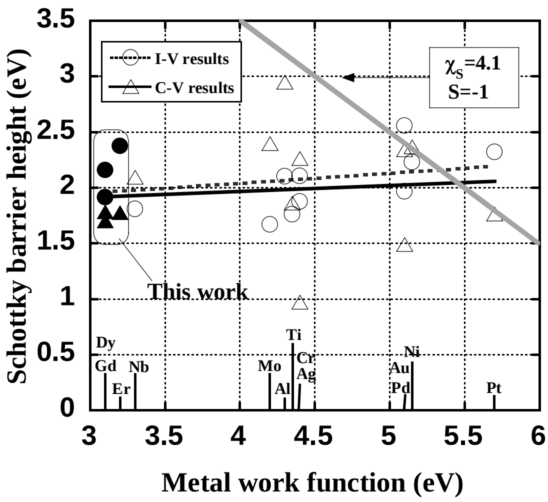

Figure 5 Metal work function dependences of $q\phi_B$ determined from I-V and C-V results.

5 Conclusion In conclusion, three kinds of rare-earth-metal films of Dy, Er, and Gd, were deposited on low-Mg-doped p-GaN, and electrical properties were characterized with I-V and C-V measurements for the first time. The effects of low ϕ_m nature on electrical characteristics and the wide range variation of ϕ_m were discussed. In the I-V characteristics, linear regions of more than one and a half orders were seen in a forward semi-log plot, and reverse break down voltages were as high as around 60 V for all samples. In the C-V characteristics, good linearity was obtained in a $1/C^2$ plot for all samples. Suppression of the leakage current succeeded by the low-Mg-doping, and good Schottky I-V and C-V characteristics were obtained. The $q\phi_B$ of Dy, Er, and Gd contacts were 1.91, 2.38, and 2.16 eV from I-V, and 1.79, 1.78, and 1.70 eV from C-V, respectively. Despite the low ϕ_m nature of these three metals, the $q\phi_B$ values are comparable with those of the transition metal contacts. The ϕ_m dependence was small (S parameters were +0.089 from the I-V and +0.054 from the C-V). These results tell us that Fermi level pinning is significantly strong for p-GaN surfaces with a conventional acid treatment. Such a strong pinning would induce a large contact resistance to p-GaN. In future study, exporting surface treatments to reduce surface states should provide a threading technology for the ohmic contacts.

Acknowledgements The authors would like to thank Professor S. Sakai of Tokushima University for providing GaN epitaxial wafers.

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